TRITIUM MIGRATION IN AN INJECTION WELL SYSTEM: DECOUPLING PHYSICAL AND CHEMICAL TRANSPORT PROCESSES IN THE FIELD

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Abstract. A series of groundwater tracer studies designed to evaluate the environmental impact associated with subsurface injection of remediated groundwater was conducted on the Department of Energy's Savannah River Site in conjunction with ongoing reclamation activities. Tritium breakthrough illustrated the heterogeneous nature of the subsurface system, suggesting that despite the coarse texture of the Coastal Plain Sediments, groundwater flow rates varied dramatically within certain regions of the aquifer. In addition, tritium breakthrough in replicate studies using similar injection rates and tracer volumes was essentially identical and differed dramatically from the transport behavior observed for anionic tracers, such as bromide (Br^-) and chloride (Cl^-), often considered conservative (i.e. non-reactive) in groundwater transport studies.

INTRODUCTION

A fundamental understanding of the physical processes associated with groundwater flow in the subsurface is critical for evaluating the potential exposure hazards associated with subsurface contamination, and developing cost-effective corrective actions that reduce such risks. However, factors such as subsurface heterogeneity with respect to hydraulic conductivity, the slow release of sorbed contaminants from the aquifer matrix, and the presence of non-aqueous phase liquids (NAPLS) complicate the design and limit the success of conventional treatment strategies, such as pump-and-treat (National Research Council, 1994; Nyer, 1996).

Groundwater tracer experiments using compounds assumed to be non-reactive with the aquifer matrix are conducted to improve our understanding of the basic physical processes controlling solute or contaminant migration by eliminating or reducing the impact of various chemical reactions such as precipitation and adsorption that complicate data analysis and interpretation. In such a case, the position of the tracer plume becomes a manifestation of the physical properties of the transmissive zone and not a function of a chemical interaction between the tracer and the porous media. However, recent studies have suggested that ionic solutes such as bromide (Br^-), chloride (Cl^-), and various halogenated benzoate derivatives, often considered conservative (i.e. non-reactive) with respect to migration behavior in groundwater transport studies, may be significantly retarded (Boggs and Adams, 1992; Seaman and Bertsch, 1995; Seaman *et al.*, 1996; Seaman *et al.*, 1995), and therefore, invalidate physical transport parameters derived from tracer studies using such compounds.

The objectives of this study were to evaluate the transport behavior of tritium, a conservative groundwater tracer, in an injection well system as a function of travel distance and depth within the receiving aquifer, and to evaluate the ability to replicate field-scale solute tracer studies in preparation for subsequent long-term solute transport studies. Technical and logistical considerations important to conducting such studies will also be discussed.

EXPERIMENTAL DESIGN

Treated groundwater from the Waste Minimization Pilot Test Project was reinjected into the water-table aquifer upgradient from the plume of origin in an effort to evaluate the impact and make specific design recommendations for the eventual implementation of the full-scale pump-and-treat reclamation system. Combining applied environmental research with the ongoing reclamation activities provided the unique opportunity to use tritium (^3H), a component of the groundwater plume that cannot be removed by the treatment process, as a conservative tracer during the injection studies and to replicate field-scale solute

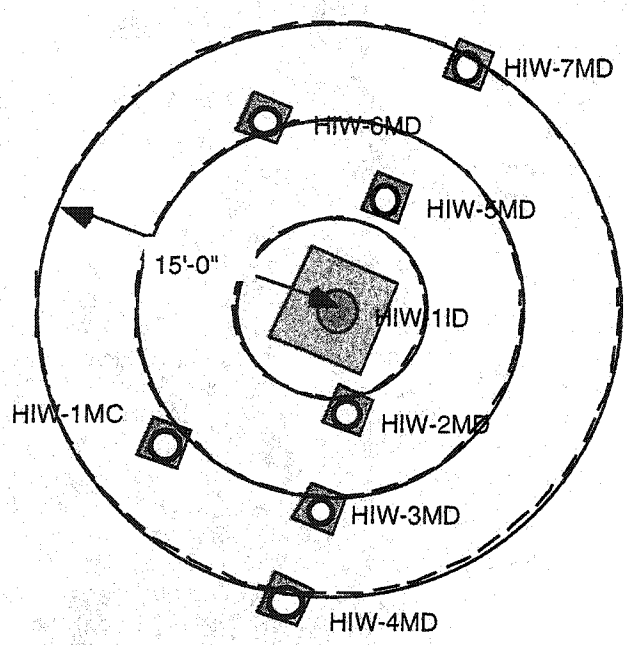

Figure 1. Relative location of injection and sampling wells at the H-Area Injection Test Site.

transport experiments under controlled conditions that are difficult to achieve in the field. Important factors such as groundwater flow and hydrodynamic dispersion associated with spatial variability within the aquifer, and subsurface colloid mobilization were evaluated as a function of injection rate, injectate composition, distance from the injection well, and depth within the receiving formation.

The H-Area Injection Test Site (HAITS), located on the Department of Energy's Savannah River Site (SRS), was designed and constructed through a collaborative effort between researchers at the University of Georgia's Savannah River Ecology Lab (SREL) and the Westinghouse Savannah River Technology Center. For clarity, each well will be identified based on the SRS system. The test site consists of a 6" ID central injection well (HIW-1ID) screened throughout the water-table aquifer (≈20 ft screened interval) and surrounded by six monitoring or sampling wells (3" ID) screened over the same interval and radially spaced at approximate distances of 5 (2MD and 5MD), 10 (3MD and 6MD), and 15 feet (4MD and 7MD) from the injection well (Fig. 1). Well HIW-1MC, located within the study site and screened within the first confined aquifer underlying the water table aquifer, was used for monitoring water depth to confirm the effectiveness of the confining layer in restricting injection of the treated groundwater to the water-table aquifer.

To avoid the introduction of colloidal artifacts (i.e. drilling mud) or the creation of preferential flow paths between closely spaced wells or sampling zones within a given well, the monitoring wells were installed using a hollow-stem auger. After augering to the desired depth (≈ 60 ft.), the well casing was inserted within the auger stem and the auger plug was displaced prior to withdrawing the stem from around the well casing. This allowed the formation to cave in around the well casing. The screened interval for each monitoring well was further divided into three discrete sampling zones or depths, with deepest zone designated as Zone 1, using an inflatable packer system (Solinst Inc., Canada). Each of the three sampling zones within a well was equipped with a bladder pump (QED Inc., Ann Arbor, MI) that could be pumped independently or in unison with one or both of the other pumps within a well.

Each tracer experiment consisted of injecting tracer-free water through the central well for approximately 24 hours at a fixed rate of 15 gpm to establish a forced gradient and reduce the level of solutes in the vicinity of the sampling wells to enhance the ability to resolve injectate tracer components from the slightly elevated levels of background solutes at the test site. Tracer injection volumes ranged from 900 to 10,000 gallons and contained tritium levels ranging from 300 to 2,000 $pC_i\,mL^{-1}$. However, discussion will be limited mainly to initial breakthrough studies involving 900 gallon pulses of tracer solution. After injection of the treatment solution, injection of tracer-free water continued for approximately 5 days to displace the tracer solution past the most distant sampling wells within the test site.

Sampling zones within each well were pumped continuously at a minimal velocity (≤ 200 mL min^{-1}) to reduce the impact of sampling on the groundwater mounding associated with injection, the volume of groundwater brought to the surface, and the generation of turbid groundwater samples associated with pumping at elevated flow rates. Groundwater samples were collected periodically for tracer analysis and turbidity measurements.

Flow-through water quality meters (YSI Inc., Yellow Springs, OH) were placed in-line for Zone 2 within each of the 6 sampling wells to monitor the pH, electrical conductivity (EC), and dissolved oxygen (DO) content throughout the duration of each injection experiment. Periodically, water depths were taken within the injection well, each of the 6 dedicated sampling wells, and three additional monitoring wells in the vicinity of the test site to observe hydraulic mounding during the course of injection as an indication of formation damage (i.e.

reduced hydraulic conductivity), a common problem affecting pump-and-treat systems.

RESULTS AND DISCUSSION

Tracer concentrations were plotted in maximum dimensionless terms (C/Co) reflecting the groundwater sample concentration divided by the concentration of the inlet solution (Co). For comparison, predicted tritium breakthrough intervals are included in the Figures based on the following simplifying displacement assumptions: a constant injection rate, uniform flow at a given radial distance from the injection well, uniform formation bulk density and porosity (i.e. 0.392 cm^3 cm^{-3}) throughout the test site (Looney *et al.*, 1987), and a fixed depth of the transport zone (i.e. 20 ft.). Initial injection studies consisted of 900 gallon tracer pulses (≈300 pCi mL^{-1}) followed by continuous injection of tracer-free water at a constant rate throughout the duration of the study.

Tritium breakthrough in well HIW-2MD illustrates the complex flow patterns within the receiving aquifer (Fig. 2). The solid line represents the ideal arrival time and concentration history expected for a non-reactive tracer moving through the formation under the above assumptions with no dispersive mixing, analogous to piston flow in one dimensional transport studies. In contrast, however, the maximum detected tritium concentration arrived earlier than initially predicted within the upper sampling zone, Zone 3, and later than expected within Zones 1 and 2. In addition to differences in flow velocity between the three zones, differences in the overall shape of the breakthrough curve and the maximum recovered concentration indicated variations in the degree of dispersive mixing occurring within and possibly between the three zones.

For well HIW-5MD, tritium breakthrough was similar within all three sampling zones displaying only minor

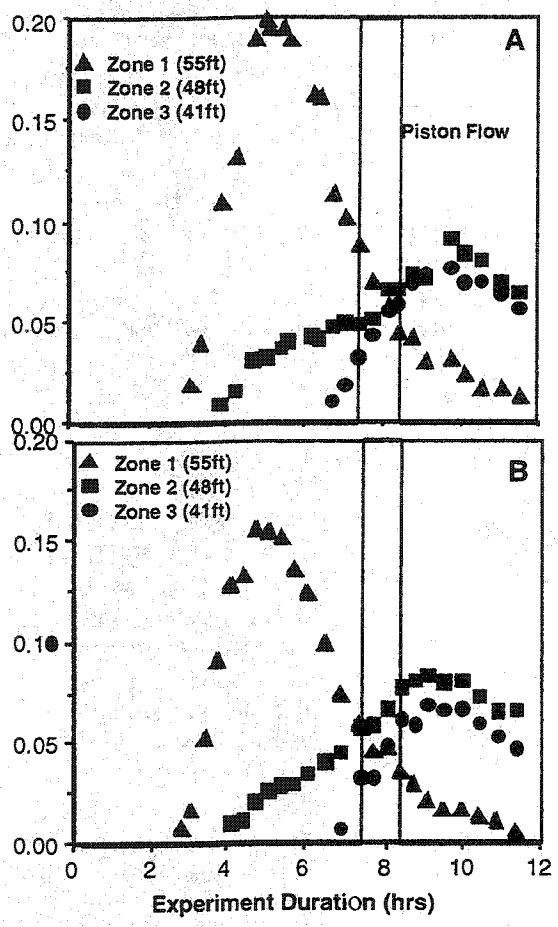

Figure 2. Tritium breakthrough at various depths within well HIW-2MD for replicate injections of 900 gallon tracer pulses (≈300 pCi mL^{-1}). Concentration scales are expanded to show similarities in breakthrough behavior. Solid lines represent the breakthrough duration for tritium under idealistic conditions.

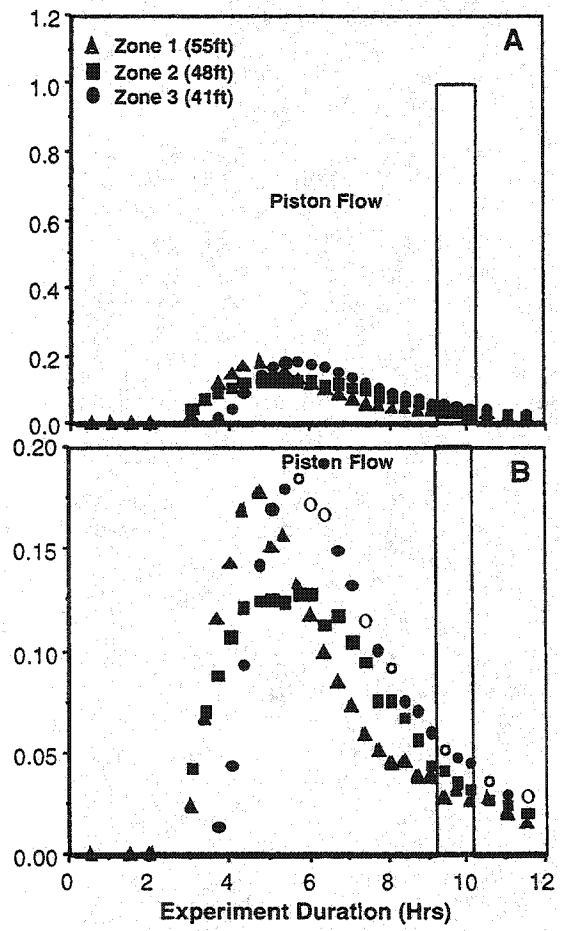

Figure 3. Tritium breakthrough in well HIW-5MD at three sampling depths (A). Solid lines represent ideal breakthrough without dispersive broadening. Scale expanded to emphasize similar breakthrough patterns (B).

differences in maximum tritium concentration and dispersive broadening between zones (Fig. 3). However, a similar degree of dilution observed for well HIW-2MD Zone 3 as indicated by maximum tritium breakthrough was also observed throughout well HIW-5MD (Fig. 3B). The early arrival of tritium for all zones within well HIW-5MD compared to the idealized breakthrough suggests that either the effective transmissive porosity differs greatly from the porosity estimates used to calculate travel times, or a strong directional dependence with respect to the initial travel paths of the injected solutions which differs from the uniform radial assumption. As seen for well HIW-2MD in Figure 2, subsequent injection studies under similar conditions confirmed the ability to replicate tritium breakthrough results in well HIW-2MD and wells spaced at greater distances.

The high degree of dispersive spreading observed at even the closest sampling wells, HIW-2MD and HIW-5MD, made it impossible to resolve the 900 gallon tritium tracer pulses or evaluate the retardation behavior of Br^- at greater travel distances. As expected, the maximum detected concentration of tritium decreased and the breakthrough peaks became broader within a given sampling zone for longer travel distances in studies using larger tritium pulses.

Breakthrough in terms of electrical conductivity (EC) monitored in the field for Zone 2 of each sampling well using the YSI units or measured in the lab for discrete samples taken for tracer analysis mimicked tracer anion breakthrough (data not shown). This supports the previous assertion by Seaman et al. (1995, 1996) that electrical conductivity provides a simple analytical technique for evaluating the breakthrough of ionic tracer solutions using pulses that are considerably more concentrated in terms of ionic solutes than the native (i.e. tracer-free) groundwater composition. The composition of the tracer solution may change as a function of various sorption and exchange reactions, but the breakthrough in terms of solution equivalents or electrical conductivity will remain as conservative as any initial ionic component.

CONCLUSIONS

The complex nature of most groundwater systems makes it difficult to experimentally separate and evaluate physical and chemical processes controlling contaminant migration at the field scale. Breakthrough trends for tritium over even short transport distances differed dramatically from the idealized case, displaying a strong directional and depth dependence under the elevated flow gradient associated with subsurface injection. Subsequent studies using common anions such as Br as tracers in addition to tritium demonstrated the difficulty in distinguishing non-conservative transport behavior in systems that display such variability with respect to hydrodispersive and advective transport. Within such systems, it becomes impossible to distinguish breakthrough behavior associated with non-linear sorption reactions from complex flow behavior associated with hydraulic heterogeneity in the absence of a truly conservative groundwater tracer. Additional injection experiments are currently planned to evaluate the transport behavior, feasible limitations and appropriate field conditions under which a variety of other groundwater tracers, including stable isotopes such as deuterium (^2H) and ^{18}O and Noble gases such as argon and krypton, can be used as conservative tracers for systems where health and regulatory concerns restrict the use of tritium.

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